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Devgan

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(54) **ISOLATION OF RF SIGNALS USING OPTICAL SINGLE SIDE BAND MODULATION COMBINED WITH OPTICAL FILTERING**

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H04B 10/556 (2013.01)

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CPC ***H04B 10/5563*** (2013.01)

(58) **Field of Classification Search**
USPC 398/115–117
See application file for complete search history.

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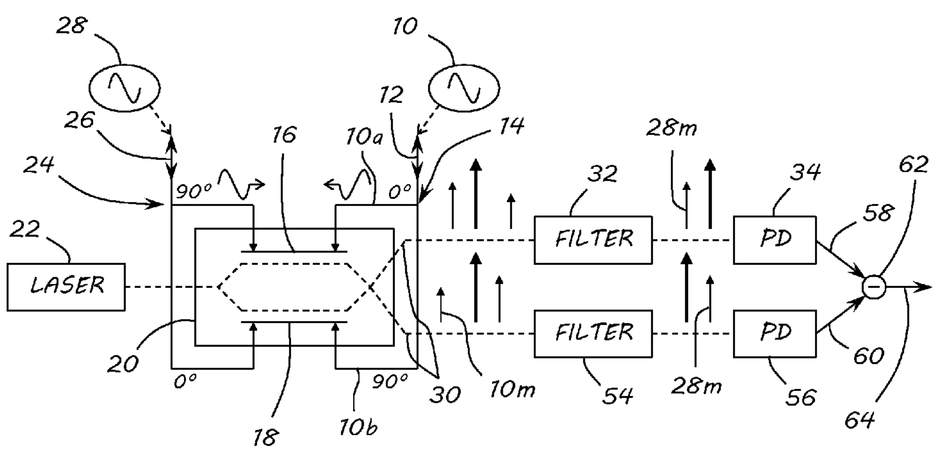
(57) **ABSTRACT**

A method and apparatus for isolating an RF signal are provided. A first RF signal is received and passed to an input of a 90 degree hybrid. An output of the 90 degree hybrid is connected to a first waveguide and a second output is connected to a second waveguide of an optical modulator. A second RF signal is received and passed to an input of a second 90 degree hybrid. An output of the second 90 degree hybrid is connected to the second waveguide and a second output is connected to the first waveguide of the optical modulator. The optical modulator is biased to produce single side band optical outputs of the RF signals. The single side band optical outputs are passed to an optical notch filter to remove one of the side band outputs. The other of the side band optical outputs is converted to an electrical signal.

6 Claims, 3 Drawing Sheets



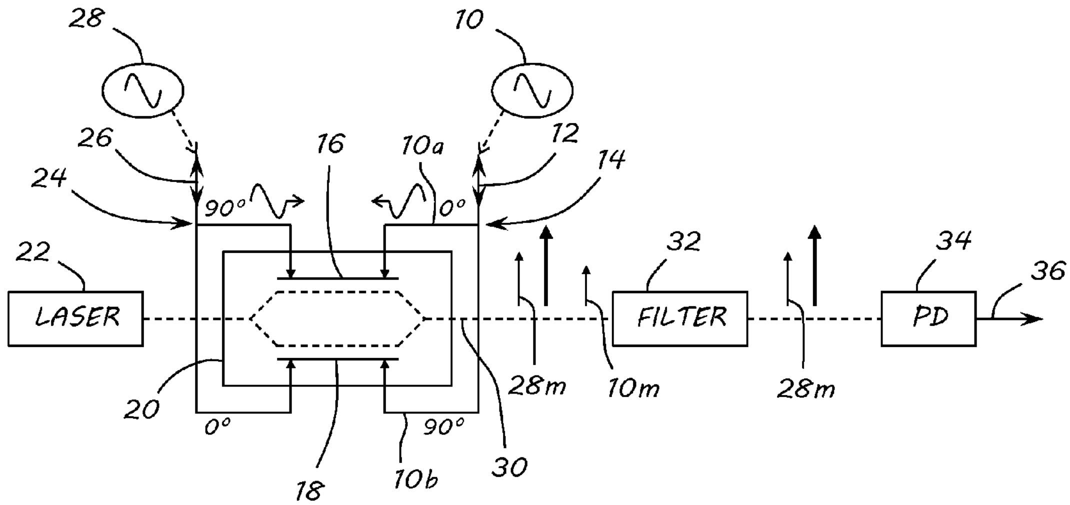

28
10
26
16
10a
12
14
24
90°
0°
22
32
34
36
LASER
FILTER
PD
20
28m
10m
28m
0°
90°
30
18
10b

FIG. 1

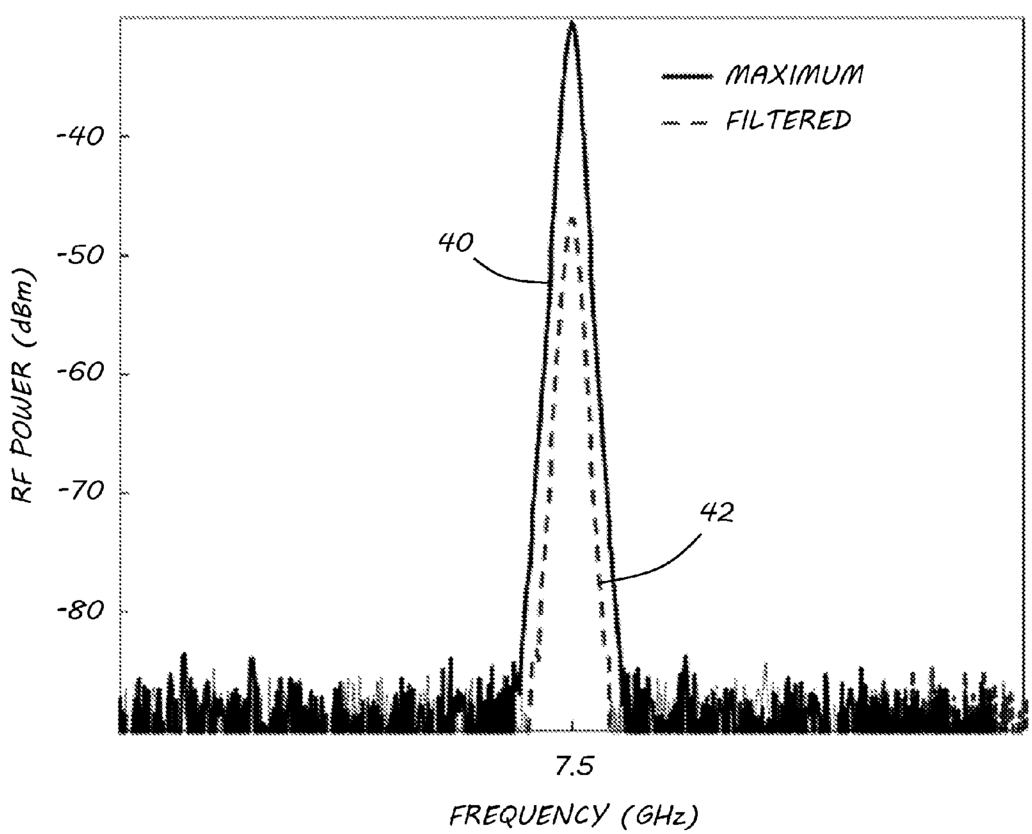
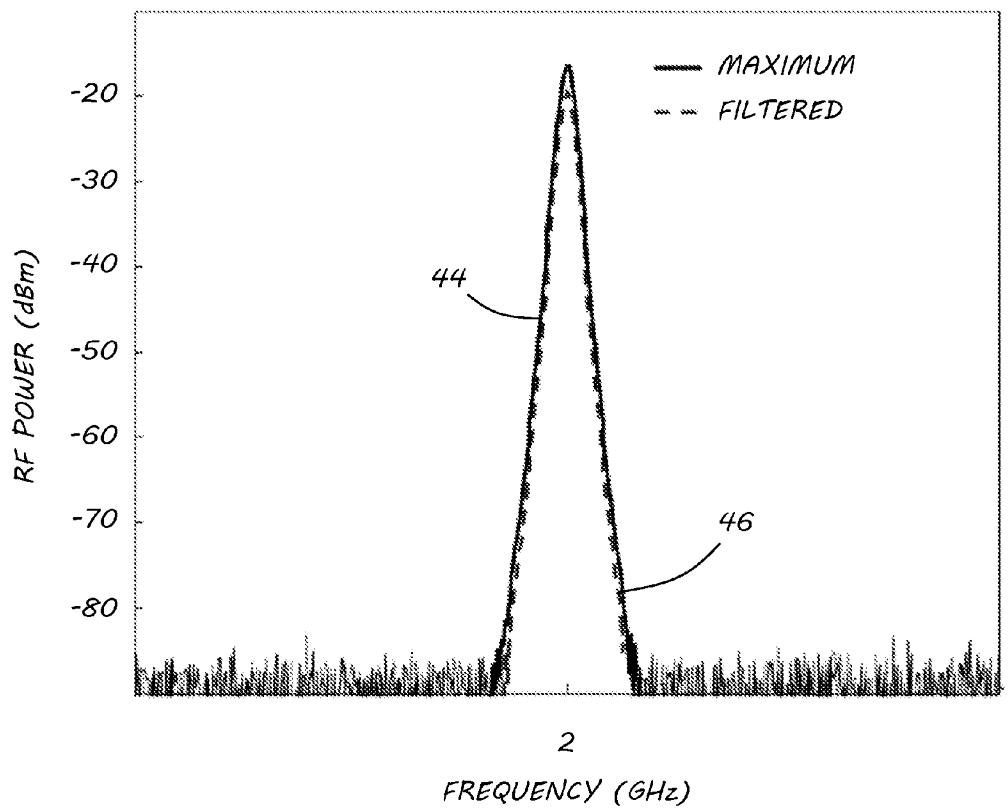
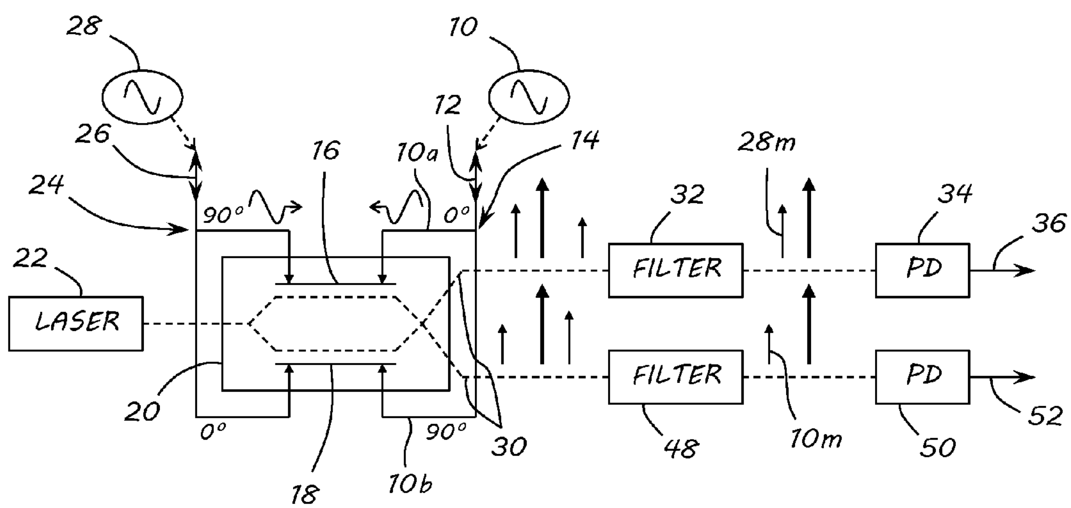

MAXIMUM
FILTERED
-40
-50
-60
-70
-80
40
42
RF POWER (dBm)
7.5
FREQUENCY (GHz)

FIG. 2



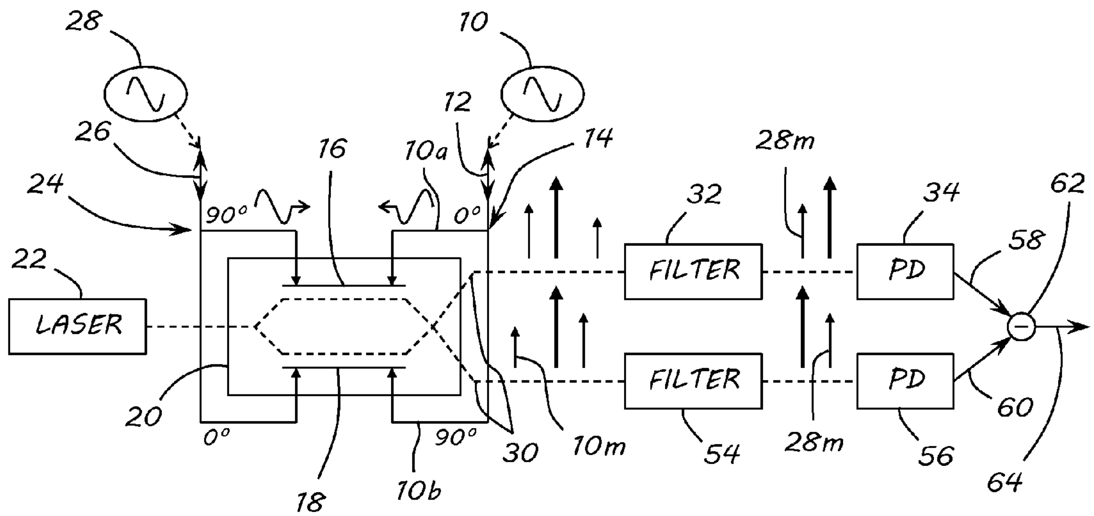
MAXIMUM
FILTERED
-20
-30
-40
-50
-60
-70
-80
RF POWER (dBm)
44
46
2
FREQUENCY (GHz)

FIG. 3



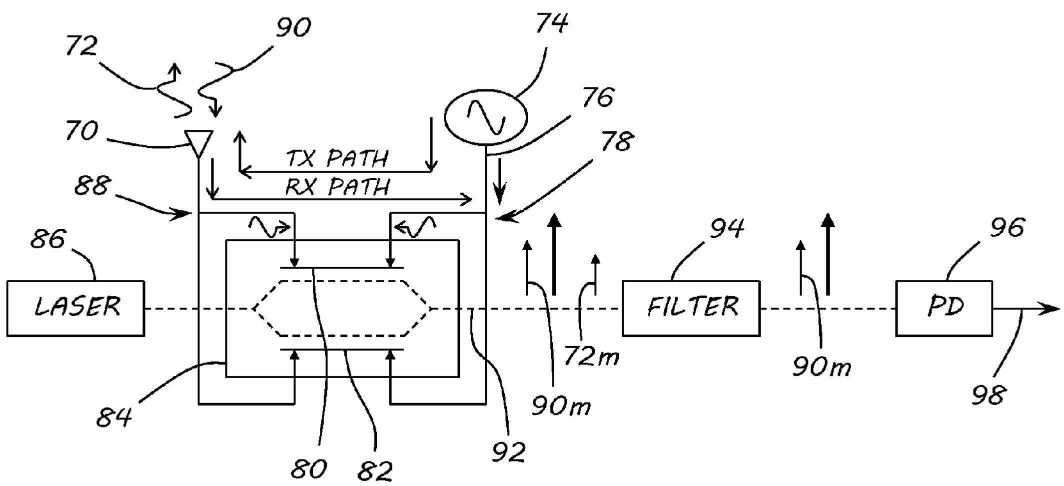
28
10
12
26
16
10a
14
28m
24
90°
0°
32
34
36
22
FILTER
PD
LASER
FILTER
PD
20
0°
90°
30
48
10m
50
52
18
10b

FIG. 4



28
10
12
26
16
10a
14
28m
24
90°
0°
32
34
62
58
22
FILTER
PD
LASER
FILTER
PD
20
0°
90°
30
10m
54
28m
56
60
64
18
10b

FIG. 5



72
90
74
70
76
78
TX PATH
RX PATH
88
86
94
96
LASER
FILTER
PD
72m
90m
84
90m
98
80
82
92

FIG. 6

ISOLATION OF RF SIGNALS USING OPTICAL SINGLE SIDE BAND MODULATION COMBINED WITH OPTICAL FILTERING

RIGHTS OF THE GOVERNMENT

The invention described herein may be manufactured and used by or for the Government of the United States for all governmental purposes without the payment of any royalty.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention generally relates to isolating RF signals and, more particularly, to isolating RF signals with optical modulation.

2. Description of the Related Art

For RF signals in the microwave frequency range and higher, traditional electronic techniques for isolation between RF paths have been limited. Methods have been investigated to improve the isolation by using either multiple circulators or matched pairs of circulators with antennas. Photonic techniques provide multiple advantages over electronic techniques, one of them being large instantaneous bandwidths. A photonic solution to RF isolation would allow for increased bandwidths and higher isolation over electronic techniques. The use of a bi-directional signal interface has been demonstrated using an optical modulator for transmit and receive functions. Further work has been shown to use this system with high isolating between the RF transmit and RF receive ports. One method for transporting RF signals over a photonic link involves single-side-band modulation. By using single side band modulation, a previous demonstration has shown that two different RF signals can be single side band modulated such that one signal is on the opposite side of the optical carrier than the other signal. Further demonstrations have shown multiple signals can be placed on either side of the optical carrier, as well as mixing baseband and microwave signals on either side of the carrier.

Even with the work done in this area, there is a need in the art for better methods of isolating RF signals.

SUMMARY OF THE INVENTION

Embodiments of the invention provide a method of isolating an RF signal. In these embodiments, a first RF signal may be received and passed to an input of a first 90 degree hybrid. A first output of the first 90 degree hybrid electrically may be connected to a first electrical waveguide of an optical modulator and a second output of the first 90 degree hybrid electrically may be connected to a second electrical waveguide of the optical modulator. A second RF signal may be received and passed to an input of a second 90 degree hybrid. A first output of the second 90 degree hybrid may be electrically connected to the second electrical waveguide of the optical modulator and a second output of the second 90 degree hybrid electrically may be connected to the first electrical waveguide of the optical modulator such that the second 90 degree hybrid is in a complementary configuration as compared to the first 90 degree hybrid. The optical modulator may be biased to produce single side band optical outputs of the first and second RF signals. The optical single side band optical outputs of the first and second RF signals may then be passed to an optical notch filter to remove one of the single side band optical outputs of the first and second RF signals. The remaining single side band optical output of the first and second RF signals may then be to an electrical signal.

In an exemplary implementation of the method, consistent with embodiments of the invention, a first port may be configured to receive a first RF signal and may be electrically connected to a first 90 degree hybrid. Additionally, a second port may be configured to receive a second RF signal and may also be electrically connected to a second 90 degree hybrid in a complementary configuration with respect to the first 90 degree hybrid. An optical modulator having a first and a second electrical waveguide may be optically coupled to a laser. The first and second waveguides may be DC biased to produce single side band optical outputs of the first and second RF signals. The first electrical waveguide electrically may be connected to a first output of the first 90 degree hybrid and a further electrically connected to a first output of the second 90 degree hybrid. The second electrical waveguide electrically may be connected to a second output of the first 90 degree hybrid and a further electrically connected to a second output of the second 90 degree hybrid. The optical modulator is configured to upconvert the first RF signal to an optical carrier frequency and co-propagate with an optical field of the laser and further configured to upconvert the second RF signal to the optical carrier frequency and counter-propagate with the optical field of the laser. An optical notch filter may be optically connected to the optical modulator and configured to remove one of the single side band optical outputs of the first and second RF signals. Finally, a photodetector may be optically connected to the optical notch filter and configured to convert the remaining single side band optical output of the first and second RF signals to an electrical signal.

In another exemplary implementation of the method, consistent with embodiments of the invention, RF signals simultaneously transmitted and received on a simultaneous transmit and receive antenna may be isolated. A transmit source may be configured to generate a transmitted RF signal and electrically may be connected to the simultaneous transmit and receive antenna. A first 90 degree hybrid may be electrically connected to the transmit source and configured to receive the transmitted RF signal. A second 90 degree hybrid in a complementary configuration with respect to the first 90 degree hybrid electrically may also be connected to the simultaneous transmit and receive antenna and configured to receive a received RF signal. An optical modulator having a first and a second electrical waveguide may be optically coupled to a laser. The first and second waveguides may be DC biased to produce single side band optical outputs of the transmitted and received RF signals. The first electrical waveguide may be electrically connected to a first output of the first 90 degree hybrid and a further electrically connected to a first output of the second 90 degree hybrid. The second electrical waveguide may be electrically connected to a second output of the first 90 degree hybrid and a further electrically connected to a second output of the second 90 degree hybrid. The optical modulator is configured to upconvert the transmitted RF signal to an optical carrier frequency and co-propagate the signal with an optical field of the laser and further configured to upconvert the received RF signal to the optical carrier frequency and counter-propagate the signal with the optical field of the laser. An optical notch filter may be optically connected to the optical modulator and configured to remove the single side band optical outputs of the transmitted RF signal. Finally, a photodetector may be optically connected to the optical notch filter and configured to convert the single side band optical output of the received RF signal to an electrical signal.

Additional objects, advantages, and novel features of the invention will be set forth in part in the description which follows, and in part will become apparent to those skilled in the art upon examination of the following or may be learned by practice of the invention. The objects and advantages of the invention may be realized and attained by means of the instrumentalities and combinations particularly pointed out in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate embodiments of the invention and, together with a general description of the invention given above, and the detailed description given below, serve to explain the invention.

FIG. **1** is a schematic block diagram of an RF Filter consistent with embodiments of the invention;

FIG. **2** is a graph showing results of a filtered signal; and

FIG. **3** is a graph showing results of an alternate filtered signal.

FIG. **4** is a schematic block diagram of an alternate embodiment of the RF filter of FIG. **1**;

FIG. **5** is a schematic block diagram of an alternate embodiment of the RF filters of FIGS. **1** and **4**;

FIG. **6** is a schematic block diagram of an alternate embodiment of the RF filters of FIGS. **1**, **4**, and **5**;

It should be understood that the appended drawings are not necessarily to scale, presenting a somewhat simplified representation of various features illustrative of the basic principles of the invention. The specific design features of the sequence of operations as disclosed herein, including, for example, specific dimensions, orientations, locations, and shapes of various illustrated components, will be determined in part by the particular intended application and use environment. Certain features of the illustrated embodiments have been enlarged or distorted relative to others to facilitate visualization and clear understanding. In particular, thin features may be thickened, for example, for clarity or illustration.

DETAILED DESCRIPTION OF THE INVENTION

Embodiments of the invention provide a technique to isolate RF signal travelling along a common path by utilizing optical single-side-band modulation combined with optical filtering. By utilizing this technique, RF isolation may be significantly increased between counter-propagating signals, which has utility for applications including simultaneous transmit and receive.

A mathematical description of a three port system using single side band modulation is set out below. A modulator, such as a Mach-Zehnder modulator (MZM), has a transfer function given by:

$$E_{out}(t) = \frac{1}{2}[e^{i\phi_1(t)} - e^{i\phi_2(t)}]E_{in}(t) \tag{1}$$

In the case of an RF signal entering port **2** of the three port system, a phase modulation on each arm of the MZM after a 90 degree hybrid may be written as:

$$\phi_1(t) = \phi_{dc1} + \phi_{rf1}\sin(\Omega_{rf}t) \tag{2}$$

and

$$\phi_2(t) = \phi_{dc2} + \phi_{rf2}\cos(\Omega_{rf}t) \tag{3}$$

with

$$\phi_{dc1,2} = \pi\left(\frac{V_{dc1,2}}{V_{\pi,dc1,2}}\right) \tag{4}$$

and

$$\phi_{rf1,2} = \pi\left(\frac{V_{rf1,2}}{V_{\pi,rf1,2}(\Omega_{rf})}\right). \tag{5}$$

Now using a Jacobi-Anger expansion

$$e^{iz\cos\theta} = \sum_{n=-\infty}^{\infty} i^n J_n(z)e^{in\theta} \tag{6}$$

$$e^{iz\sin\theta} = \sum_{n=-\infty}^{\infty} i^n J_n(z)e^{in\theta} \tag{7}$$

the following can be written:

$$E_{carrier}(t) = \frac{\overline{E}_{in}e^{i\omega_0 t}}{2}[e^{i\phi_{dc1}} J_0(\phi_{rf1}) - e^{i\phi_{dc2}} J_0(\phi_{rf2})], \tag{8}$$

$$E_{usb,fund}(t) = \frac{\overline{E}_{in}e^{i\omega_0 t - i\Omega_{rf}t}}{2}[-e^{i\phi_{dc1}} J_1(\phi_{rf1}) - ie^{i\phi_{dc2}} J_1(\phi_{rf2})], \tag{9}$$

$$E_{lsb,fund}(t) = \frac{\overline{E}_{in}e^{i\omega_0 t + i\Omega_{rf}t}}{2}[e^{i\phi_{dc1}} J_1(\phi_{rf1}) - ie^{i\phi_{dc2}} J_1(\phi_{rf2})], \tag{10}$$

In the present case, the RF signal may be the same on both electrical waveguides so $\phi_{rf1}=\phi_{rf2}$. For the condition of single-side-band operation, there are two cases. For the upper side band to be nulled, $\phi_{dc1}=-\pi/2+\phi_{dc2}$ and for the lower side band to be nulled, $\phi_{dc1}=\pi/2+\phi_{dc2}$. For an RF signal input to port **1**, a second 90 degree hybrid may be utilized in a complementary configuration so $\phi_1(t)=\phi_{dc1}+\phi_{rf}\cos(\Omega_{rf}t)$ and $\phi_2(t)=\phi_{dc2}+\phi_{rf2}\sin(\Omega_{rf}t)$. In this configuration, the resulting fields may be written as:

$$E_{carrier}(t) = \frac{\overline{E}_{in}e^{i\omega_0 t}}{2}[e^{i\phi_{dc1}} J_0(\phi_{rf1}) - e^{i\phi_{dc2}} J_0(\phi_{rf2})], \tag{11}$$

$$E_{usb,fund}(t) = \frac{\overline{E}_{in}e^{i\omega_0 t - i\Omega_{rf}t}}{2}[ie^{i\phi_{dc1}} J_1(\phi_{rf1}) + e^{i\phi_{dc2}} J_1(\phi_{rf2})], \tag{12}$$

$$E_{lsb,fund}(t) = \frac{\overline{E}_{in}e^{i\omega_0 t + i\Omega_{rf}t}}{2}[ie^{i\phi_{dc1}} J_1(\phi_{rf1}) - e^{i\phi_{dc2}} J_1(\phi_{rf2})]. \tag{13}$$

For a single side band condition, the upper side band may be nulled when $\phi_{dc1}=\pi/2+\phi_{dc2}$) and the lower side band may be nulled when $\phi_{dc1}=\pi/2+\phi_{dc2}$. Thus, it is apparent that the RF signals at port **1** and port **2** may appear on opposite sides of the optical carrier when the bias conditions are set for single side band modulation allowing the RF signals to be separated in the optical spectrum from one another. Then, by using an optical filter, one sideband may be removed while the carrier and other sideband will pass on to the photodetector to recover the RF signal at the third port.

Turning now to FIG. **1** the above configuration may be implemented in an embodiment of the invention as follows.

An RF signal **10** at input port **12** is split by a 90 degree hybrid **14** onto two electrical waveguides **16**, **18** in a modulator **20**, such as a Mach-Zehnder modulator though other modulators or modulation techniques may also be used, with a zero degree output on waveguide **16** and a 90 degree output on waveguide **18**. The RF signal **10** counter-propagates to an optical field that is input to the modulator **20** from a laser **22**. The split signals **10***a*, **10***b* then pass down to another 90 degree hybrid **24** which is placed in a complementary arrangement to the hybrid **14**. In this embodiment, hybrid **24** has a 90 degree input connected to waveguide **16** and a zero degree input connected to waveguide **18**. Split signals **10***a* and **10***b* are then recombined and may be transmitted out a port **26**.

Port **26** may also receive another RF signal **28**. This RF signal **28** may be split by 90 degree hybrid **26**, with a 90 degree output on waveguide **16** and a zero degree output on waveguide **18**. Signal **28** will also co-propagate with the optical field of the laser **22** in the modulator **20** and counter-propagate to RF signal **10**. Similarly a recombined signal **28** may be transmitted out port **12**. Both RF signals **10**, **28** may then be upconverted onto an optical carrier frequency of the laser **22**. A DC bias may then be set for each of the electrical waveguides **16**, **18** resulting in an optical output **30** that will be single side-band.

Because RF signal **10** passes through the complementary 90 degree hybrid of RF signal **28**, RF signal **10***m* will appear on an opposite single side of the optical carrier as compared to RF signal **28***m*. The optical output **30** of the modulator **20** may then be passed through an optical filter **32** in order to remove an unwanted RF signal's sideband, while preserving the sideband of an RF signal of interest. Optical filter **32** may be a notch type optical filter for some embodiments, and in other embodiments, the notch filter may be a tunable optical notch filter. An output of the filter **32** is connected to a photodetector **34** where the RF signal **28** is recovered and then output at a port **36**. Because the RF signal is removed by the optical filter **32** before the detector, RF isolation between port **12** and port **30** is better than utilizing electrical filters after the photodetector **34** as is common in contemporary devices.

With the signal being removed by the optical filter before the detector, the RF isolation between port **12** and port **36** may be quite high. For example, in a measurement made with an RF signal **10** at 7.5 GHz input to port **12** and a second RF signal **28** at 2 GHz input at port **26**. The modulator **20** may be biased in order to set both signals into single side band modulation on either side of the optical carrier and then the optical filter may be adjusted. The RF powers associated with RF signal **10** at port **36** for the 7.5 GHz signal **10** from port **12** are illustrated in the graph in FIG. **2**. When the filter is set to maximize signal **10** from port **12**, the RF power is −30 dBm as shown by curve **40**. When the filter is set to extinguish the side band, shown by curve **42**, the RF power is −47 dBm, which is a 17 dB extinction. The graph in FIG. **3** shows the RF power at port **36** for the 2 GHz signal **28** from port **26**. When the filter is set of maximize the signal at port **26**, the RF power is −16.3 dBm as shown by curve **44**. When the filter is set to extinguish the other side band, the RF power is −19.3 dBm as shown by curve **46**. When the input power of the two signals is taken into account, the unwanted signal, from port **12** for example, is −41 dB from the power of the input signal at port **12**, taking into account the additional insertion loss of the optical filter.

In an alternate embodiment illustrated in FIG. **4**, the RF signal **10** at input port **12** is again split by the 90 degree hybrid **14** onto two electrical waveguides **16**, **18** in a modulator **20** with a zero degree output on waveguide **16** and a 90 degree output on waveguide **18**. The RF signal **10** counter-propagates to the optical field that is input to the modulator **20** from the laser **22**. The split signals **10***a*, **10***b* then pass down to another 90 degree hybrid **24** which is placed in a complementary arrangement to the hybrid **14**. Similarly, in this embodiment, hybrid **24** has the 90 degree input connected to waveguide **16** and the zero degree input connected to waveguide **18**. Split signals **10***a* and **10***b* are then recombined and may be transmitted out port **26**.

Similar to the embodiment described above, port **26** may also receive another RF signal **28**. This RF signal **28** may be split by 90 degree hybrid **24**, with a 90 degree output on waveguide **16** and a zero degree output on waveguide **18**. Signal **28** will also co-propagate with the optical field of the laser **22** in the modulator **20** and counter-propagate to RF signal **10**. Similarly the recombined signal **28** may be transmitted out port **12**. Both RF signals **10**, **28** may then be upconverted onto the optical carrier frequency of the laser **22**. A DC bias may then be set for each of the electrical waveguides **16**, **18** resulting in an optical output **30** that will be single side-band.

Because RF signal **10** passes through the complementary 90 degree hybrid of RF signal **28**, RF signal **10***m* will appear on an opposite single side of the optical carrier as compared to RF signal **28***m*. The optical output **30** of the modulator **20** may then be split with one output connected to optical filter **32** and the other to optical filter **48**. Again optical filter may be a notch type optical filter that is tuned to remove the unwanted RF signal's sideband, in this case the sideband containing signal **10***m*. The output of the filter **32** is then connected to the photodetector **34** where the RF signal **28** is recovered and then output at port **36**. Similarly, optical filter **48** may also be a notch type optical filter that is tuned to remove the unwanted RF signal's sideband, in this case the sideband containing signal **28***m*. The output of the filter **48** then connected to a photodetector **50** where the RF signal **10** is recovered and then output to a port **52**.

In an alternate embodiment illustrated in FIG. **5**, the RF signal **10** at input port **12** is again split by the 90 degree hybrid **14** onto two electrical waveguides **16**, **18** in a modulator **20** with a zero degree output on waveguide **16** and a 90 degree output on waveguide **18**. The RF signal **10** again counter-propagates to the optical field that is input to the modulator **20** from the laser **22**. The split signals **10***a*, **10***b* then pass down to another 90 degree hybrid **24** which is again placed in a complementary arrangement to the hybrid **14**. Similarly, in this embodiment, hybrid **24** has the 90 degree input connected to waveguide **16** and the zero degree input connected to waveguide **18**. Split signals **10***a* and **10***b* are then recombined and may be transmitted out port **26**.

Similar to the embodiments described above, port **26** may also receive another RF signal **28**. This RF signal **28** may be split by 90 degree hybrid **26**, with a 90 degree output on waveguide **16** and a zero degree output on waveguide **18**. Signal **28** will also co-propagate with the optical field of the laser **22** in the modulator **20** and counter-propagate to RF signal **10**. Similarly the recombined signal **28** may be transmitted out port **12**. Both RF signals **10**, **28** may then be upconverted onto the optical carrier frequency of the laser **22**. A DC bias may then again be set for each of the electrical waveguides **16**, **18** resulting in an optical output **30** that will be single side-band.

Because RF signal **10** passes through the complementary 90 degree hybrid of RF signal **28**, RF signal **10***m* will appear on an opposite single side of the optical carrier as compared to RF signal **28***m*. The optical output **30** of the modulator **20** may again be split with one output connected to optical filter **32** and the other to optical filter **54**. In this embodiment, the optical filters **32**, **54** may be a notch type optical filters that are tuned to remove the unwanted RF signal's sideband, in this case the sideband containing signal **10***m*. The output of the filter **32** is then connected to the photodetector **34** where the RF signal **28** is recovered and then output at **58**. Similarly, the output of the filter **56** then connected to a photodetector **56** where again the RF signal **28** is recovered and then output at **60**. Then using balanced photodetection of the photodetectors **34**, **56**, the signals may be combined at **62** and output to a port **64**. Combination of the same signals at port **64** may assist in achieving better performance and a stronger filtered signal.

FIG. **6** illustrates an embodiment of the invention used in a practical application utilizing a simultaneous transmit and receive (STAR) antenna **70**. An RF transmit signal **72** originating from a transmission source **74** may be received at port **76** and split by a 90 degree hybrid **78** onto two electrical waveguides **80**, **82** in a modulator **84** with a zero degree output on waveguide **80** and a 90 degree output on waveguide **82**. The transmit RF signal **72** again counter-propagates to the optical field that is input to the modulator **84** from a laser **86**. The split signals then pass down to another 90 degree hybrid **88** placed in a complementary arrangement to the hybrid **78**. In this embodiment, hybrid **88** has the 90 degree input connected to waveguide **80** and the zero degree input connected to waveguide **82**. The split signals are then recombined and may be transmitted out port the antenna **70**.

The antenna may simultaneously receive RF signal **90**. The transmitted and received signals **72**, **90** may be at the same frequency in some of the embodiments. This received RF signal **90** may also be split by 90 degree hybrid **88**, with the 90 degree output on waveguide **80** and a zero degree output on waveguide **82**. Both the transmitted and received RF signals **72**, **90** may then be upconverted onto the optical carrier frequency of the laser **86**. A DC bias may then be set for each of the electrical waveguides **80**, **82** resulting in an optical output **92** that will be single side-band with the transmitted RF signal **72***m* will appear on an opposite single side of the optical carrier as compared to the received RF signal **90***m*. The optical output **92** of the modulator **84** is connected to optical filter **94**, which is a notch type optical filter tuned to remove the sideband containing the transmitted signal **72***m*. The output of the filter **94** is then connected to a photodetector **96** where the received RF signal **90** is recovered and then output at a port **98**.

This method and apparatus provides much better isolation between two RF signals that are counter-propagating along the same path than is provided by contemporary electronic methods. The larger isolation makes it easier for applications such as simultaneous transmit and receive to be realized. The photonic system also provides much larger instantaneous bandwidth (>20 GHz) than that of contemporary electronic methods. By using a photonic link for the RF path between input and output ports, the output port is also isolated from any damaging RF powers such as from a direct lightning strike or other sources. While the present invention has been illustrated by a description of one or more embodiments thereof and while these embodiments have been described in considerable detail, they are not intended to restrict or in any way limit the scope of the appended claims to such detail. Additional advantages and modifications will readily appear to those skilled in the art. The invention in its broader aspects is therefore not limited to the specific details, representative apparatus and method, and illustrative examples shown and described. Accordingly, departures may be made from such details without departing from the scope of the general inventive concept.

What is claimed is:

1. An apparatus for isolating RF signals, the apparatus comprising:

a first port configured to receive a first RF signal;

a first 90 degree hybrid electrically connected to the first port;

a second port configured to receive a second RF signal;

a second 90 degree hybrid in a complementary configuration with respect to the first 90 degree hybrid electrically connected to the second port;

a laser;

an optical modulator optically coupled to the laser and having a first and a second electrical waveguide, the first and second waveguides DC biased to produce single side band optical outputs of the first and second RF signals, the first electrical waveguide electrically connected to a first output of the first 90 degree hybrid and a further electrically connected to a first output of the second 90 degree hybrid, the second electrical waveguide electrically connected to a second output of the first 90 degree hybrid and a further electrically connected to a second output of the second 90 degree hybrid;

the optical modulator configured to upconvert the first RF signal to an optical carrier frequency and co-propagate with an optical field of the laser and further configured to upconvert the second RF signal to the optical carrier frequency and counter-propagate with the optical field of the laser;

a first optical notch filter optically connected to the optical modulator and configured to remove one of the single side band optical outputs of the first and second RF signals;

a first photodetector optically connected to the optical notch filter and configured to convert the other of the single side band optical outputs of the first and second RF signals to an electrical signal;

a second optical notch filter optically connected to the optical modulator and configured to remove the one of the single side band optical outputs of the first and second RF signals; and

a second photodetector optically connected to the second optical notch filter and configured to convert the one of the single side band optical outputs of the first and second RF signals to an electrical signal.

2. The apparatus of claim **1**, wherein the optical notch filter is a tunable filter.

3. The apparatus of claim **1**, wherein the optical modulator is a Mach-Zehnder modulator.

4. An apparatus for isolating RF signals, the apparatus comprising:

a first port configured to receive a first RF signal;

a first 90 degree hybrid electrically connected to the first port;

a second port configured to receive a second RF signal;

a second 90 degree hybrid in a complementary configuration with respect to the first 90 degree hybrid electrically connected to the second port;

a laser;

an optical modulator optically coupled to the laser and having a first and a second electrical waveguide, the first and second waveguides DC biased to produce single side band optical outputs of the first and second RF signals, the first electrical waveguide electrically connected to a first output of the first 90 degree hybrid and a further electrically connected to a first output of the second 90 degree hybrid, the second electrical waveguide electrically connected to a second output of the first 90 degree hybrid and a further electrically connected to a second output of the second 90 degree hybrid;

the optical modulator configured to upconvert the first RF signal to an optical carrier frequency and co-propagate with an optical field of the laser and further configured to upconvert the second RF signal to the optical carrier frequency and counter-propagate with the optical field of the laser;

a first optical notch filter optically connected to the optical modulator and configured to remove one of the single side band optical outputs of the first and second RF signals; and

a first photodetector optically connected to the optical notch filter and configured to convert the other of the single side band optical outputs of the first and second RF signals to an electrical signal;

a second optical notch filter optically connected to the optical modulator and configured to remove the one of the single side band optical outputs of the first and second RF signals;

a second photodetector optically connected to the second optical notch filter and configured to convert the other of the single side band optical outputs of the first and second RF signals to an electrical signal; and

a combiner electrically coupled to the first photodetector and the second photodetector, wherein the first photodetector and the second photodetector are balanced.

5. The apparatus of claim **4**, wherein the optical notch filter is a tunable filter.

6. The apparatus of claim **4**, wherein the optical modulator is a Mach-Zehnder modulator.

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